# kt SPIRiT for Ultra-Fast Cardiac Cine Imaging with Prospective or Retrospective Cardiac Gating

**P. Lai[1], M. Lustig[2,3], A. C. Brau[1], and S. Vasanawala[4]**

[1]Applied Science Laboratory, GE Healthcare, Menlo Park, CA, United States, [2]Electrical Engineering, Stanford University, Stanford, CA, United States, [3]Electrical Engineering and Computer Science, University of California, Berkeley, CA, United States, [4]Radiology, Stanford University, Stanford, CA, United States

**Introduction:** Cardiac cine imaging requires ultra-fast acquisition of high spatiotemporal resolution images within a short breathhold, which is difficult for conventional parallel imaging (PI). Recent progress has increased the achievable acceleration mainly from two perspectives. First, various kt methods [1,2,3] have proven capable of providing reasonable image quality at high acceleration factors by additionally exploiting temporal correlations in dynamic imaging. Second, a few approaches combining PI and compressed sensing (CS) [4,5,6], such as $L_1$SPIRiT [6], have shown potential in acceleration beyond coil capability. The purpose of this work was to develop a reconstruction algorithm for highly-accelerated cardiac imaging with prospective (PG) or retrospective (RG) gating based on coil sensitivity and spatiotemporal sparsity in dynamic medical images.

**Theory:** kt SPARSE [7] first introduced CS to dynamic imaging, using Fourier transform ($F$) to sparsify signal along the short time dimension ($t$). However, Fourier transform is not an efficient sparse transform and requires periodic motion in a complete cardiac cycle which is not available with PG. Alternatively, we construct a hybrid image in [$x, t \cdot y$] (Fig.1.c) from cine image series in [$x, y, t$] (Fig.1.b), with the synthesized dimension $t \cdot y$ obtained by concatenating all t and y points at the same x location using a "rewinding" ordering scheme (Fig.1.a). Owing to continuous cardiac motion, this hybrid cardiac image exhibits smooth signal transition in ($x, t \cdot y$) for both PG and RG and is highly compressible. For accelerated imaging, incoherent artifacts in ($y, t$) originating from random kt undersampling manifests now as incoherent artifacts along $t \cdot y$, which could be effectively resolved by wavelet CS (Fig. 1.d).

**Methods:** Based on the above theory, we extend the concept of $L_1$SPIRiT to cardiac cine imaging and propose a new method, kt SPIRiT, which utilizes k-space correlations and exploits compressibility of spatial & temporal signals simultaneously. Fig. 2 illustrates the flow chart of kt SPIRiT reconstruction, iteratively performing the following 6 steps:

**Step 1.** view sharing with shrinking $t$-window ($VS_{st}$) in the first $AF$ ($AF$: acceleration factor) iterations: a wide t-window (width=$AF$ cardiac phases) was used for the first iteration to generate an initial solution with most undersampling artifacts resolved. The $t$-window shrinks by 1 cardiac phase in each iteration and quickly reduces to 1 (no view sharing) to avoid temporal blurring in the final solution. By this means, kt SPIRiT converges much faster without sacrificing reconstruction accuracy.

**Step 2.** resynthesize k-space data using a GRAPPA-like convolution kernel ($G$) representing k-space correlations [8], calculated from time-averaged center k-space data. For faster computation, this processing is alternatively performed with image-domain multiplications [9].

**Step 3.** synthesize a hybrid image ($X_h$) from cine image series ($X$). To avoid consistently positioning the temporal fusing boundary in $t \cdot y$ at the 1st and last cardiac phases, cine image series was circularly shifted by 1 cardiac phase in each iteration.

**Step 4.** compressed sensing: the hybrid image ($X_h$) was transferred to sparse domain using wavelet ($\psi$), where $min \ ||\cdot||_1$ was pursued by softthresholding ($T$).

**Step 5.** regenerate cine image series $X$ from $X_h$.

**Step 6.** data fidelity: set acquired k-space data to sampled values ($x_0$).

For RG, an additional step should be added before the above iteration to remap acquired data to proper cardiac phases using closest neighbor interpolation.

The proposed method was evaluated in comparison with another two representative kt methods, kt GRAPPA [2] and kt SPARSE. For this purpose, cardiac cine imaging was conducted on 6 healthy volunteers (3 PG & 3 RG) on GE 1.5T in short- and long-axis views. Full k-space was collected using a 2D cine FIESTA sequence and an 8-channel cardiac coil. Typical imaging parameters were: ~320×220 mm$^2$ FOV; 1.25×1.3 mm$^2$ spatial resolution; 5 mm slice thickness; 40 ms temporal resolution; 60° flip angle; TR/TE: 4.0/2.0 ms. Accelerated data acquisition for kt methods was simulated with various acceleration factors by downsampling full k-space offline. For kt GRAPPA, 15 center k-space lines were fully sampled as calibration signals. For kt SPARSE/SPIRiT, variable density sampling was used with 3× acceleration in center 21 k-space lines and higher acceleration in outer k-space. Poisson-disk sampling [6] in k-t space was used in both center and outer k-space regions. Images were reconstructed in Matlab and compared based on visual assessment and reconstruction accuracy analysis.



Fig. 1. Sparsity in hybrid (x, t·y) image



Fig. 2. kt SPIRiT Reconstruction



Fig. 3. Upper: RG, late diastole; Lower: PG, 1st cardiac phase



Fig. 4. Mean artifact power from all subjects vs. net reduction (left to right: $AF$ = 4-8×)

**Results:** Fig. 3 compares different reconstructions with RG (upper) and PG (lower). kt GRAPPA with 7× (b, f) suffers from significant temporal blurring and ghosting artifacts, while kt SPARSE (c, g) exhibits considerable loss of myocardium edge sharpness. In comparison, kt SPIRiT (d, h) produces image quality very similar to full k-space references (a, e) in both cases. The improvement of kt SPIRiT was observed to be most evident during intensive motion and at 1st/last frames. As shown in Fig. 4, both kt GRAPPA and kt SPARSE generate larger errors than kt SPIRiT at high $AF$'s. The overhead of calibration data acquisition substantially reduces the net reduction factor for kt GRAPPA. Furthermore, the reconstruction accuracy of kt SPIRiT degrades very slowly with increasing acceleration.

**Discussion:** This work demonstrated a new algorithm, kt SPIRiT, supporting highly-accelerated cardiac imaging. The proposed method requires only general random sampling rather than special k-t sampling patterns [1] and therefore is compatible with retrospective gating requiring cardiac phase remapping. Also, CS in hybrid images avoids the large error at the 1st/last frames for Fourier transform with prospective gating and enables exploiting spatiotemporal sparsity simultaneously. Our results show that kt SPIRiT can achieve higher image quality and reconstruction accuracy compared to methods expoiting kt space correlations or signal sparsity alone (e.g. kt GRAPPA & kt SPARSE). Although demonstrated for 2D cardiac imaging only, this method can be extended to 3D and other dynamic imaging applications.

**References:** [1] Tsao, MRM 2003:1031; [2] Huang, MRM 2005, 54:1172; [3] Jung, MRM 2009, 61:103; [4] King, ISMRM 2008:1488; [5] Liu, ISMRM 2008:3154; [6] Lustig ISMRM, 2009:334; [7] Lustig, ISMRM 2007:2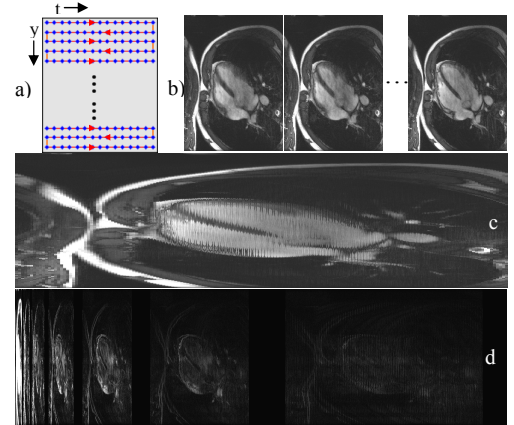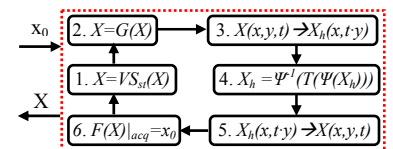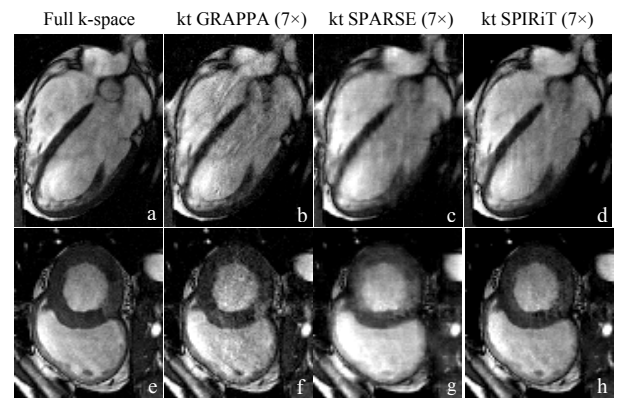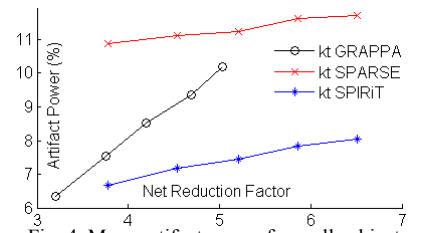420; [8] Lustig, ISMRM 2007:333; [9] Brau, MRM 2008, 59:382.